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The Evolution of Supernovae in the Winds of Massive Stars

Vikram Dwarkadas

ASCI FLASH Center, Dept. of Astronomy and Astrophysics, University of Chicago, 5640 S Ellis Ave, Chicago IL 60637

Abstract

We study the evolution of supernova remnants in the circumstellar medium formed by mass loss from the progenitor star. The properties of this interaction are investigated, and the specific case of a 35 $M_\odot$ star is studied in detail. The evolution of the SN shock wave in this case may have a bearing on other SNRs evolving in wind-blown bubbles, especially SN 1987A.

1.1 INTRODUCTION

Type II Supernovae are the remnants of massive stars (M > 8 $M_\odot$). As these stars evolve along the main sequence, they lose a considerable amount of mass, mainly in the form of stellar winds. The properties of this mass loss may vary considerably among different evolutionary stages. The net result of the expelled mass is the formation of circumstellar wind-blown cavities, or bubbles, around the star, bordered by a dense shell. When the star ends its life as a supernova, the resulting shock wave will interact with this circumstellar bubble rather than with the interstellar medium. The evolution of the shock wave, and that of the resulting supernova remnant (SNR), will be different from that in a constant density ambient medium.

In this work we study the evolution of supernova remnants in circumstellar wind-blown bubbles. The evolution depends primarily on a single parameter, the ratio of the mass of the shell to that of the ejected material. Various values of this parameter are explored. We then focus on a specific simulation of the medium around a 35 $M_\odot$ star, and show how pressure variations within the bubble can cause the shock wave to be corrugated. Different parts of the shock wave collide with the dense shell at different times. Such a situation is reminiscent of the evolution of the shock wave around SN 1987A.

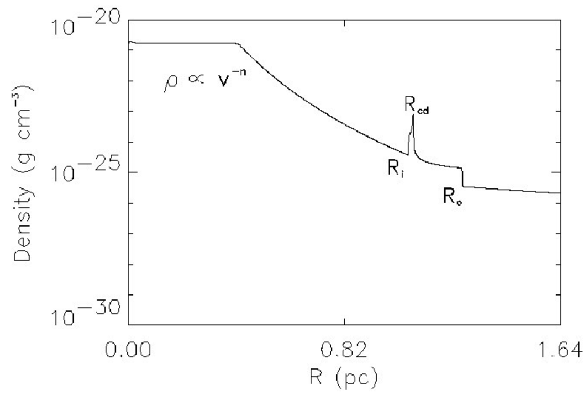

Fig. 1.1. The density profile of the ejected SN material in the initial stages, from a numerical calculation. Interaction of the ejecta with the ambient medium gives rise to an outer shock (R_o), inner shock (R_i) and contact discontinuity (R_{cd}).

1.2 The SN Profile

The interaction of the SN shock wave with the surrounding medium in the early stages depends on the density profile of the SN and the surrounding medium. The density structure of the ejecta depends on the structure of the star and the shock acceleration in the outer layers (Chevalier & Fransson 1994). Although observational information on valid density profiles is scarce, numerical simulations, especially for SN 1987A, as well as semi-analytic calculations show that the ejecta density profile in the outer layers can be approximated by a power-law in radius (Fig 1.1; see Chevalier & Fransson 2003 for further information). This approximation is used in the current work.

1.3 Structure of the Circumstellar Medium (CSM)

The general structure of a wind-blown nebula was first elucidated by Weaver et al. (1977). In the simplest, two-wind approximation, a fast wind from a star collides with slower material emitted during a previous epoch, driving a shock into the ambient medium. The pressure of the post-shock material causes the freely flowing fast wind to decelerate, driving a second shock that travels inwards towards the center. A double-shocked structure, separated by a contact discontinuity, is formed. Figure 1.2 shows the density and pressure profiles from a simulation of a wind-blown bubble. Proceeding in the direction of increasing radius from the central star we find the follow-

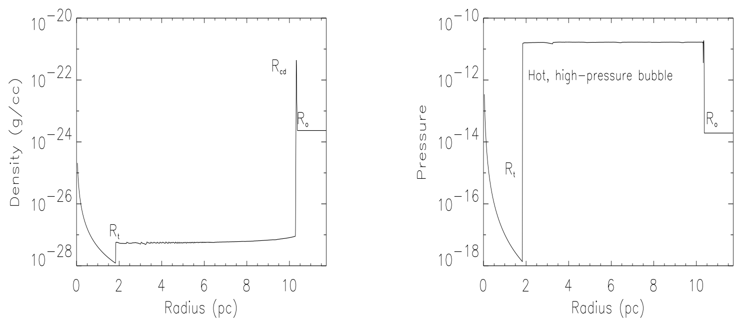

Fig. 1.2. a) Density and b) Pressure profiles from a numerical simulation of a wind-blown bubble around a massive star.

ing regions delineated: freely flowing fast wind, inner or wind-termination shock (R_t), shocked fast wind, contact discontinuity (R_{cd}), shocked ambient medium, outer shock (R_o) and unshocked ambient medium.

1.4 SNR-Circumstellar Medium Interaction

The interaction of the SN ejecta with the freely expanding wind gives rise to a double-shocked structure, consisting of a forward shock driven into the wind and a reverse shock moving into the ejecta. Given the low density interior of the wind-blown bubble, the luminosity of the remnant is lower than if the explosion were to occur within the ISM. It is clear that in general most of the bubble mass is contained within the dense circumstellar (CS) shell. Thus the interaction of the ejecta with this shell is crucial to determining the evolution of the remnant. This interaction depends on a single parameter $\Lambda = \frac{M_{shell}}{M_{ejecta}}$, the ratio of the shell mass to the ejecta mass.

An exploration of the interaction of SN shock waves with CS bubbles described by the Weaver et al. (1977) model shows (eg. Dwarkadas 2002), that for small values of the parameter $\Lambda \leq 1$, the structure of the density profile is important (Figure 1.3a-d). Just after the shock-shell interaction has taken place, the density *decreases* outwards from the reflected shock to the contact discontinuity. However as the evolution proceeds, the supernova remnant begins to "forget" the existence of the shell, and loses memory of the interaction. The density structure changes to reflect this, and begins to *increase* from the reflected shock to the contact discontinuity. In this case it takes about 15 doubling times of the radius for the remnant to forget the interaction with the shell (Fig 1.3d). In another few doubling times, the

remnant density profile will resemble that of a SNR evolving directly in the ambient medium. When computing the X-ray or optical emission from the remnant, which are functions of the density of the shocked material, it is imperative that this changing density structure be taken into account.

As the value of the parameter Λ increases, i.e. the mass of the wind-blown shell increases compared to the ejecta mass, the energy transmitted by the remnant to the shell also increases. Energy transfer to the shell becomes dynamically important, and the remnant evolution is speeded up. The reflected shock moves rapidly through the ejecta, and complete thermalization of the ejecta is achieved in a shorter time as compared to the SN reverse shock thermalizing the ejecta. If the value of Λ is large, the SN shock may become radiative, and the kinetic energy is converted to thermal energy. In extreme cases, the remnant may then go directly from the free-expansion stage to the radiative stage, by-passing the classical adiabatic or "Sedov" stage.

1.5 A 35 M$_\odot$ Star

Using mass-loss data kindly provided to us by Norbert Langer, we have modeled the evolution of the medium around a 35 $M_\odot$ star, and the further interaction of the shock wave with this medium once the star explodes as a SN. The star goes through the sequence O-Star, Red-Supergiant Star (RSG) and Wolf-Rayet (WR) star. Below we describe, mainly through images of the fluid density, the subsequent evolution of the CSM around the star.

Main Sequence (MS) Stage

The wind from the star, with velocity of a few (3-4) thousand km/s and mass loss rate on the order of $10^{-7} M_\odot$/yr expands into a medium with density of about 1 particle/cc, giving rise to a bubble about 74 pc in radius. Fig 1.4 shows (from left to right) a time-sequence of density images of the formation of the MS bubble. Note that the main-sequence shell is unstable to a Vishniac-type thin-shell instability. The density inhomogeneities lead to pressure fluctuations which propagate within the interior, which soon develops into a turbulent state. The evolution of these perturbations distinguishes our results from those of Garcia-Segura et al. (1996), who considered the MS shell to be stable and therefore assumed spherical symmetry. However the 2D structure is quite different, and has significant implications for the succeeding evolution of the bubble.

Red-Supergiant (RSG) Stage

In the RSG stage the wind velocity falls to a low value of about 75 km/s, whereas the mass loss rate jumps up to a few times $10^{-5} M_\odot$/yr. A new

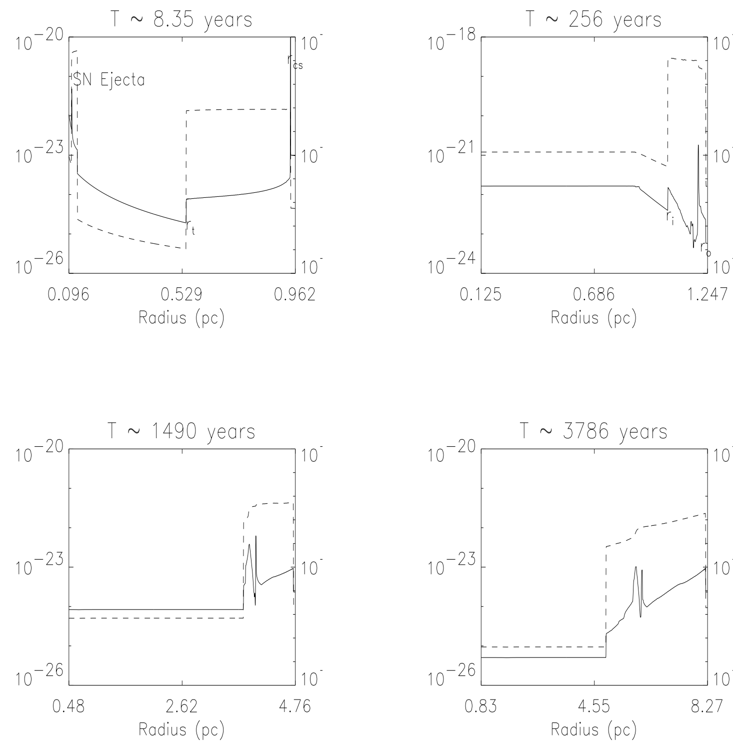

Fig. 1.3. Snapshots in time from a simulation of SN ejecta interacting with a CS bubble. The mass in the circumstellar shell is 14% of that in the ejecta. The solid lines display density, with the scale given on the LHS. The dashed lines displays the pressure, with the scale given on the RHS. All units are CGS. The time is given at the top of each figure in years. The labels (a) to (d) in the text go in order of increasing time, from top to bottom and left to right.

pressure equilibrium is established, and a RSG shell is formed in the interior, which is also unstable to thin-shell instabilities. Fig 1.5 (frames 1 and 2) shows images of the density during the RSG evolution.

Wolf-Rayet (WR) Phase

The wind velocity in the WR phase climbs back up to almost 3000 km/s, whereas the mass loss rate drops by only a factor of a few from the RSG stage. The momentum of the WR wind is then about an order of magnitude larger than that of the RSG wind, and the wind pushes the RSG shell outwards, simultaneously causing it to fragment (Fig 1.5, frame 3). The RSG wind material is mixed in with the rest of the MS material (Fig 1.5, frame 4), a key result since the RSG wind velocity was so low that the material by itself could not have gone very far. Out of $\sim 26M_{\odot}$ of material

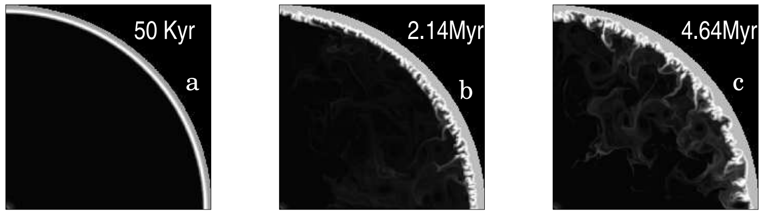

Fig. 1.4. Time-sequence of images of the formation of the CSM around a 35 $M_{\odot}$ O-Star during the main sequence.

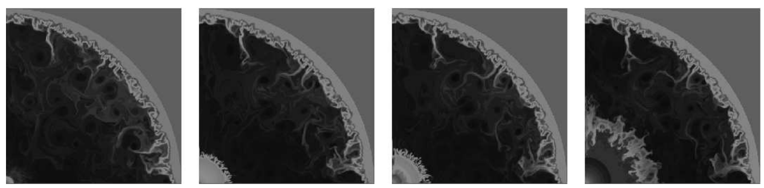

Fig. 1.5. The first two density images from left show the formation of the inner RSG shell, which is unstable to thin-shell perturbations.The next two display the onset of the WR wind and its collision with the RSG shell, causing it to fragment and the RSG material to be mixed in with the rest of the nebula.

lost in the wind, about 19 $M_{\odot}$ is lost in the RSG stage, so much of the material within the nebula is composed of matter lost in the RSG phase.

SN-CSM Interaction

At the end of the WR phase the stellar mass is about 9.1 $M_{\odot}$. We assume that about 1.4 $M_{\odot}$ remains as a neutron star, and the remaining mass is ejected in a supernova explosion, with a density profile that goes as a power-law in the outer parts, with a power-law index of 7. The interaction soon forms the usual double-shocked structure. In Figure 1.6 we show images of the fluid pressure. This variable is chosen to clearly illustrate the shocked region between the inner and outer shocks. The shock starts off as a spherical shock (Fig 1.6a), but the pressure within the turbulent interior soon causes it to become rippled (Fig 1.6b). The corrugated shock structure collides with the boundary of the bubble in a piecemeal fashion (Fig 1.6c), and as each small part collides with the outer boundary, a reflected shock arises in that region. There exist many pieces of reflected shock that arise from various interactions, have different velocities, and consequently reach the inner boundary at different times. The thermalization of the material then occurs in different stages, and X-ray images will reveal a very complicated structure which will differ considerably on scales of tens to hundreds of years.

HST images of SN 1987A have revealed the presence of various bright

spots around the circumstellar ring, presumably due to the interaction of the SN shock front with the equatorial ring structure (eg. Sugerman et al. 2002). The collision of a highly wrinkled shock with various parts of the circumstellar shell, leading to the different parts brightening up at different times, is very similar to the current situation of the shock front in SN 1987A. The case of SN 1987A however is more complicated in that the region interior to the ring is presumed to be an ionized HII region (Chevalier & Dwarkadas 1995). It is possible though that an aspherical HII region would serve only to accentuate the asphericity in the shock front. The simulation described herein is for a 35 $M_{\odot}$ star, whereas in 87A the progenitor star was less massive, and possibly part of a binary system. Nevertheless the similarities are striking, and suggest the existence of such wrinkled shock fronts when SNe evolve in wind-blown bubbles.

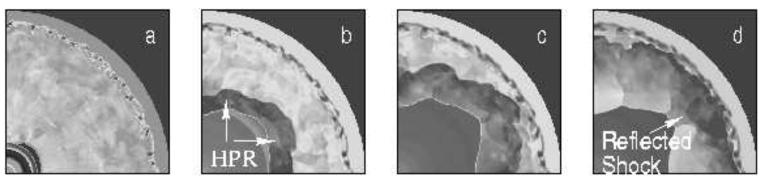

Fig. 1.6. Time-sequence of pressure images of the interaction of the SNR shock with the WR bubble. HPR represents the high-pressure region between the inner and outer SNR shocks. Note the rippled structure of the outer shock from frame 2 onwards, and its interaction at different times with various parts of the shell.

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References

Chevalier, R. A., & Fransson, C., 2003, *in Supernovae and Gamma-Ray Bursters, Lecture Notes in Physics 598*, ed. K. Weiler, (Springer-Verlag).
Chevalier, R. A., & Fransson, C., 1994, *ApJ*, **420**, 268.
Chevalier, R. A., & Dwarkadas, V. V., 1995, *ApJ*, **452**, L45.
Dwarkadas, V. V., 2002, in *Interacting Winds from Massive Stars, ASP Conference Proceedings, Vol. 260*. Edited by A. F. J. Moffat and N. St-Louis, (San Francisco: ASP), 141
Garcia-Segura, G., MacLow, M.-M., & Langer, N., 1996, *A&A*, **316**, 133.
Sugerman, B., et al., 2002, *ApJ*, **572**, 209
Weaver, R., McCray, R., Castor, J., et al., 1977, *ApJ*, **218**, 377.